Adaptation and Technological Change

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The purpose of this talk is to provide a brief summary of the state of the science on the influences of adaptation on the social cost of climate change. Specifically, the charge was to discuss (not necessarily in this order):

(1) relevant studies on the observed or potential effectiveness of adaptive measures, and on private behaviors and public projects regarding adaptation;
(2) relevant studies on how to forecast adaptive capacity;
(3) how adaptation and technical change could be represented in an IAM (for at least one illustrative sector);
(4) whether the information required to calibrate such a model is currently available, and, if not, what new research is needed; and
(5) how well or poorly existing IAMs incorporate the existing body of evidence on adaptation.

A tall order, but important to get our arms around since estimates of the net impact of climate change could be significantly higher if adaptation is not taken into account.[1]

As elaborated below, a number of general insights have resulted from our brief foray into this topic that have implications for the development of a future research program in this area. First, modeling adaptation is inherently difficult given the nature of the adaptation process, requiring advancements in modeling techniques. Second, although there has been good empirical work done on impacts and adaptation costs, the coverage is limited requiring heroic efforts to translate the results into model parameters. More work is needed to bridge the gap between models and empirical studies. Lastly, adaptation-related technological change is generally lacking in current models but could significant lower adaptation cost estimates. This stems from a general lack of understanding of the process related to this type of technological change. More empirical work is needed in this area.

What is unique about the adaptation process that justifies the need to add features to existing integrated assessment models (IAMs)? First, adaptation is in response to current or anticipated impacts and comes in different forms: (a) reactive (e.g., changes in heating/cooling expenditures; treatment of disease; shifts in production); and (b) proactive (e.g., infrastructure construction (e.g., seawalls); early warning systems; water supply protection investments. In some IAMs adaptation would occur endogenously in reaction to changes in prices due to climate impacts—e.g., more power plants built to deal with increases in demand for air conditioning; shifts in production in reaction to higher prices of factors negatively impacted by climate change. However, many adaptation activities that would occur in reality, such as investment in flood protection, would not occur in a simulated model unless there is explicit representation of climate damages to induce reactive expenditures and proactive investments.

Second, unlike mitigation investments where investments today result in reductions today, proactive adaptation investments are made today to provide protection against possible future impacts. Thus, adaptation investment decisions are inherently intertemporal and therefore

[1] For the U.S., Mendelsohn et al. (1994) estimates that the net impact of climate change on the farming sector will be 70% less if adaptation is included while Yohe et al. (1996) estimates that the net impact on coasts will be approximately 90% less (Mendelsohn (2000)).

models need to include intertemporal decision making for proactive adaptation investments, in order to trade off future damages and current adaptation investment expenditures. Not only are we making intertemporal adaptation decisions, we are specifically making proactive adaptation investments under uncertainty. Whether we invest and how much to invest all depends on our expectations regarding future impacts and how we value the future. Therefore, we need a model that allows for intertemporal decision-making under uncertainty.

Climate damages and adaptation strategies are locally- or regionally-based. Therefore, ideally the model will include regional detail or will apply a method to aggregate up to a more coarse regional representation. Climate damages and adaptation expenditures are also sector specific—e.g., certain sectors will be impacted more than others and adaptation expenditures will be directed at specific sectors (e.g., electric power, construction). Thus, a model with sectoral detail or a way to aggregate these sector-specific impacts and expenditures is desirable.

The demand for adaptation solutions will induce adaptation-related technological change. Do inducements for adaptation-related technological change differ markedly from mitigation-related technological change, requiring a different modeling approach? To the extent that adaptation activities may be region or sector specific, markets for new adaptation techniques will be smaller than for new mitigation techniques, making private sector R&D investments less attractive. Given this, as well as the case that adaptation investments are largely public infrastructure investments, distinguishing between public R&D and private R&D may be important. Note that this is more than a question of simply basic versus applied science, but driven by the nature of demand for the final product, much in the same way that the government finances most R&D for national defense. Thus, the model needs to be capable of distinguishing between private and public investments and include mechanisms of public revenue raising to fund these projects.

To summarize, to be able to capture adaptation strategies, an ideal IAM would include the following features:

- Explicit modeling of climate damages/impacts
- Intertemporal decision making under uncertainty
- Endogenous technological change
- Regional and sectoral detail for impacts and adaptation strategies
- Connection with empirical work on impacts and adaptation

Is it feasible or even desirable to have all of these features represented in a single model, since transparency is lost as more features are added? It is important to measure the trade-offs:

- How much of this needs to be specifically represented in the model and how could be represented outside of the model
- To cite Jake Jacoby: “different horses for different courses.” Do we need a suite of models each designed to capture a subset of these features?
- How important is each of these features to the social cost of climate change? Sensitivity analysis could be useful here to assess whether we even need to worry about including certain features.

To answer these questions, it is useful to first survey what features currently exist in IAMs. A number of modeling approaches have been taken to capture impacts and adaptation. Computable general equilibrium (CGE) models have the advantage of providing sectoral and regional detail and capturing the indirect effects of impacts and adaptation. Thus, given its structure, CGE models can more easily accommodate regional and sectoral-specific damage functions. Most CGE models, however, do not include the type of intertemporal decision making required to model proactive adaptation investment decisions, given the computational demands required by a model with detailed regions and sectors. However, there have been a number of CGE models that have been used to estimate the cost of climate change impacts; for example,

- DART (Deke et al, 2001)—to study the cost of coastal protection
- FARM (Darwin and Tol, 2001; Darwin et al, 1995)—includes detailed land types to study the effects of sea level rise and impacts of climate change on agriculture.
- GTAP-E/GTAP-EF (Bosello et al, 2006; Bigano et al, 2008; Rosen, 2003)—has been used to study induced demand for coastal protection; effects of rising temperatures on energy demand (Bosello et al, 2007); health effects of climate change (Bosello et al, 2006); effects of climate change on tourism. Focuses on one impact at a time.
- Hamburg Tourism Model (HTM) (Berittella et al, 2006; Bigano et al, 2008)—used to study the effect of climate change on tourism.
- ICES (Eboli et al, 2010)—models multiple impacts simultaneously: impacts on agriculture, energy demand, human health, tourism, and sea level rise.

Another set of models used to study climate change impacts and adaptation fall under the category of optimal growth models. These models include intertemporal optimization but typically lack sectoral and regional detail given the computational demands this would require. These include:

- DICE/RICE (Nordhaus, 1994; Nordhaus and Yang, 1996; Nordhaus and Boyer, 2000)—DICE comprises one region, one aggregate economy, and one damage function aggregating many impacts. RICE comprises 13 regions, each with its own production function and damage function.
- AD-DICE/AD-RICE (de Bruin et al, 2009)—DICE/RICE model with adaptation. Adaptation investment added as a decision variable which lowers damages and faces an adaptation cost curve. Residual damages are separated from protection costs in the damage function.

There are also a number of simulation models that have been developed to study the effects of climate change impacts. The major difference from CGE and optimal growth models is that simulation models do not optimize an objective function, such as intertemporal utility. Instead, these models represent a number of interconnected relationships that allow for studying the propagation of perturbations to the system. Two widely used simulation models are:

- PAGE (Plambeck and Hope, 1997; Hope, 2006)—PAGE comprises eight regions each with its own damage functions for two impact sectors (economic and non-economic). The authors use information on impacts from IPCC (2001) to generate model parameter values related to impacts. In addition, PAGE stochastically models catastrophic events where the probability of an event

increases when temperature exceeds a certain threshold. Simple adaptation is included in the model which reduces damages. Assumes developed countries can reduce up to 90% of economic impacts while developing can reduce up to 50%. All regions can reduce up to 25% of non-economic impacts.
- FUND (Tol et al, 1995; Tol, 1995)—referred to as a "policy optimization" model. Exogenous variables include population (from the World Bank), GDP per capita (from EMF 14), and energy use. Endogenous variables include atmospheric concentrations, radiative forcing, climate impacts (species loss, agriculture, coastal protection, life loss, tropical cyclones, immigration, emigration, wetland, dryland), emission reductions (energy or carbon efficiency improvements, forestry measures, lower economic output), ancillary benefits (e.g., improved air quality), and afforestation. The model comprises 9 regions with game theoretics and eight market and non-market sectors, each with its own calibrated damage function. Adaptation is modeled explicitly in the agricultural and coastal sectors, and implicitly in other sectors such as energy and human health where the wealthy are assumed to be less vulnerable to the impacts of climate change. No optimization in the base case—just simulation. In the optimization case, the model is choosing the optimal level of emissions reductions by trading off costs and benefits of reductions.

Another class of models involves hybrid combinations of the above model types. For example,

- Bosello and Zhang (2006) couple an optimal growth model with the GTAP-E model of Burniaux and Truong (2002) to study the effects of climate change on agriculture
- Bosello et al (2010) couple the ICES CGE model with an optimal growth model (AD-WITCH) to study adaptation to climate change impacts.
- AD-WITCH (Bosello et al, 2010)—an optimal growth model with detailed bottom-up representation of the energy sector. Comprises 12 regions where the following seven control variables exist for each region: investment in physical capital, investment in R&D, investment in energy technologies, consumption of fossil fuels, investment in proactive adaptation, investment in adaptation knowledge; and reactive adaptation expenditure. These alternative uses of regional income compete with each other.

To parameterize these models, most modeling teams look to empirical studies of impacts and adaptation and are faced with similar frustrations. First, as elaborated in Agrawala and Fankhauser (2008), the empirical work in the area of adaptation is severely lacking. The authors find that although information exists on adaptation costs at the sector level, certain sectors (e.g., coastal zones and agriculture) are studied more heavily than others. Second, most empirical studies are not done with modeling applications in mind. Most modelers find themselves forced to devise methods to scale up from the regional and sectoral results generated by empirical studies.

There have been a few recent studies that have attempted to summarize the empirical work on adaptation costs; e.g.,

- Agrawala and Fankhauser (2008)—provides a critical analysis of empirical work on adaptation costs. Tables summarize empirical sectoral studies on adaptation costs. Sectors include coastal zones, agriculture, water resources, energy demand, infrastructure, tourism and public health.
- World Bank (2010)—report from The Economics of Adaptation to Climate Change (EACC) study. Seven sector-specific studies: infrastructure, coastal zones, water supply and flood protection, agriculture, fisheries, human health, extreme weather events. Provides detailed estimates of adaptation costs; some generated using dose response functions with engineering estimates and some generated from sector-specific models.
- UNFCCC (2007)—regional studies (Africa, Asia, Latin America, and small island developing States) on vulnerability; current adaptation plans/strategies; future adaptation plans/strategies. Most information from national communications to the UNFCCC, regional workshops, and expert meetings.

A few modeling teams have made serious attempts to integrate existing empirical work on adaptation into their model; for example,

- AD-DICE/AD-RICE: starts with damage functions of Nordhaus and Boyer (2000) and uses empirical studies to separate residual damages from adaptation costs. Various studies on adaptation measures for certain sectors (i.e., agriculture and health) and estimates of adaptation costs from existing studies are used. Also, other model results—e.g., results from FUND—are used to estimate adaptation costs in response to sea level rise. Empirical studies to separate residual damages from adaptation costs are not available for many of the sectors—i.e., other vulnerable markets; non-market time use; catastrophic risks; settlements—so assumptions were made in order to separate the damage costs. However, these sectoral estimates are ultimately aggregated up to one damage cost number and one adaptation cost number to fit with the one sector structure of the model.
- AD-WITCH: Uses empirical information from the construction of damage functions in Nordhaus and Boyer (2000), the studies in Agrawala and Fankhauser (2008); and UNFCCC (2007) to separate residual damages from adaptation costs. Similar to AD-DICE, using these empirical studies to separate the damage estimates in Nordhaus and Boyer (2000) into residual damages and adaptation costs.

Comparing this brief survey of existing work in this area with the list of required modeling features needed to model adaptation, a couple of key research voids stand out. First, none of these models include decision making under uncertainty, and for good reason. It is difficult to do. Optimal growth models like DICE with intertemporal decision making are deterministic and fully forward-looking. Past approaches to modify such a model to be stochastic usually entail the following steps:

1) Create multiple States of the World (SOWs), each with different parameter assumptions and different probabilities of occurrence;
2) Index all variables and equations in the model by SOW;
3) Add constraints to the decision variables so that for all time periods before information is revealed, decisions must be equal across SOWs.

The problem with this approach is that it rapidly becomes a very large constrained nonlinear programming problem, and often the model will not converge to a solution for more than a trivial number of SOWs. The general problem of decision making under uncertainty is a stochastic dynamic programming problem that requires the exploration of a large number of samples of outcomes in every time period. The challenge is to fully explore the sample space while keeping the model computationally tractable. Promising on-going research by Mort Webster and his team at MIT could offer an alternative approach to modeling decision making under uncertainty. Webster's NSF-funded project team is currently developing a formulation based a new approach called Approximate Dynamic Programming, introduced by Powell (2007) and others. This approach implements dynamic programming models by iteratively sampling the state space using Monte Carlo techniques, approximating the value function from those samples, and using approximate value functions to solve for an approximate optimal policy, then repeating. This approach has been used successfully in other contexts for very large state spaces. Mort Webster's team is currently developing an ADP version of the ENTICE-BR model to study R&D decision making under uncertainty.

Second, adaptation-related technological change is largely absent in current models. Most models are calibrated using existing knowledge of adaptation strategies and costs with no allowance for improvements in these strategies and technologies. AD-WITCH (Bosello et al, 2009) does attempt to account for this by including investment in adaptation knowledge as a decision variable that competes with other types of investment. Investments in adaptation knowledge accumulate as a stock which reduces the negative impact of climate change on gross output. However, the lack of empirical studies on adaptation-related technological change limits the modelers' ability to calibrate their model based on empirical knowledge. In the case of AD-WITCH, adaptation knowledge investments only relate to R&D expenditures in the health care sector where empirical data exist. This suggests that more empirical research in this area is desperately needed.

Third, differences in adaptive capacity or differences in the ability of regions to adapt to climate change are also important to capture in model analyses given the implications for distributional effects but are typically not represented in existing models. The FUND model implicitly captures adaptive capacity in the energy and health sectors by assuming wealthier nations are less vulnerable to climate impacts. However, it seems that only one model, AD-WITCH, attempts to explicitly capture adaptive capacity through the inclusion of investments in adaptation knowledge as a decision variable. Not only does this variable capture R&D investments in adaptation-related technologies as discussed in the previous paragraph, it also captures expenditures to improve the region's ability to adapt to climate change. Issues arise, however, when the model is calibrated since the modelers were only able to identify one source of qualitative information on adaptive capacity (i.e., the UNFCCC (2007) report discussed above) which only covers four aggregate regions (Africa, Asia, small island developing States, and Latin America). Assumptions were then made to translate this information to the regional representation and model parameters in AD-WITCH.

Lastly, another area where empirical work to inform models is lacking is in the dynamics of recovery from climate change impacts. Most models represent climate damages as a reduction in economic output which is assumed to recover over time. Empirical work on thresholds and time to recover including factors that influence these variables could help inform models on the type of dynamics that should be captured in impact and adaptation analyses. Also, better techniques to translate results from empirical studies to models are needed since the sectoral and regional detail of empirical studies does not typically align with the sectoral and regional detail in models. In general, to address the disconnect between empirical studies and modeling needs, we as a research community need to devise better ways to facilitate communication between empirical researchers and modelers.

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